High Energy Polarized Beams: Status and Challenges

M. Bai

Forschungszentrum, Juelich

PSTP Workshop, Sept, 2015

Outline

- History of polarized beams
  - Motivation
  - Types of polarized beams
- Status of high energy polarized beams
  - The art of making high energy polarized beams
  - Achieved performance of polarized beams
- Future plans of high energy polarized beams and challenges
- Summary

The Discovery of Spin

- the concept was first proposed by Wolfgang Pauli in 1925. Then, Ralph Kronig, George Uhlenbeck and Samuel Goudsmit jointly proposed a physical interpretation of particles spinning around their own axis
- in 1927, the mathematical theory was worked out in depth by Pauli
- first experimentally demonstrated by Stern and Gerlach
- Paul Dirc derived relativistic quantum dynamics, where electron spin was the essential part

Wolfgang Pauli

Stern-Gerlach

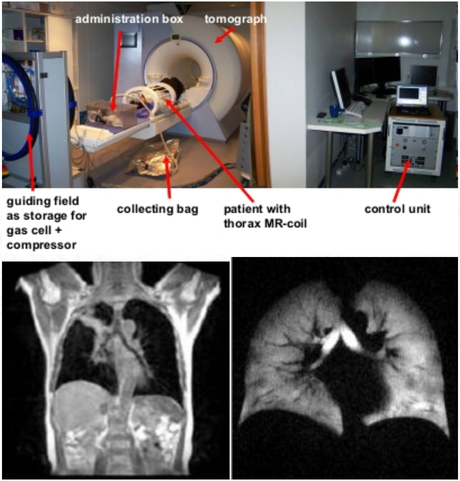
Paul Dirc

Why polarized beams?

polarized beams provide an unique tool

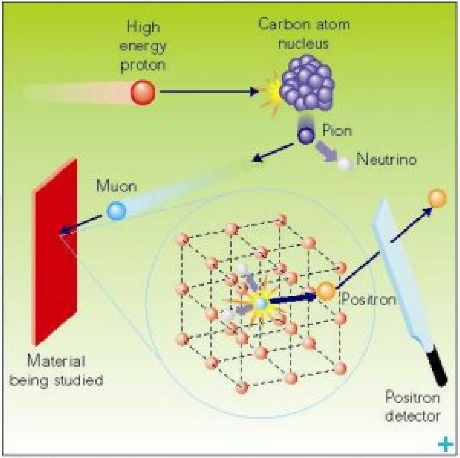
- to probe the fundamental structure of matter
- to unveil the deep secret of nucleon spin structure
- precision measurements
  - study fundamental interactions: hadron physics at COSY
  - measure muon magnetic moment: g-2 experiment
  - to search for electric dipole moment: under investigation
- powerful diagnostic tool
  - N.M.R image using polarized He-3: Prof. Masayoshi Tanaka's presentation in session 15
  - Muon Spin Relaxation/Restoration/Resonance
    - a technique of using the muon spin to look at structural and dynamical processes in the bulk of a material on an atomic scale
    - Worldwide facilities: ISIS@UK, PSI@SW, Triumf@CA
  - precise energy calibration for high energy beams

Polarized He-3 N.M.R.



http://www.ag-heil.physik.uni-mainz.de/34_ENG_HTML.php

How μSR works?



http://nmi3.eu/muon-research/characteristics-of-muons.html

The making of polarized beams: source

- polarized electron source
  - 1965-1972: photoionization from potassium/lithium atomic beams, reached 58% – 78% polarization
  - 1990s: development of GaAs polarized electron source
  - presently, high current electron source with high polarization is under development for ILC and EIC
    - ★ BNL's Gattling Gun to reach high current 50mA with $> 80\%$
- polarized hadron source
  - Polarized atomic beam ion source
  - optically pumped polarized ion source
    - ★ the working horse for RHIC. Reached 10mA with $85 - 90\%$ polarization
  - presently, polarized He-3 source are under development
    - ★ EBIS based with optical pumping $He3$ gas: James Maxwell (MIT) in session 8
    - ★ laser driven: Ilhan Engin (Forschungszentrum Juelich) in session 15

The making of polarized beams: accelerators

- **spin dynamics in a synchrotron: Thomas-B.M.T. Equation** [L. H. Thomas, Phil. Mag. 3, 1 (1927); V. Bargmann, L. Michel, V. L. Telegdi, Phys, Rev. Lett. 2, 435 (1959)]

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{e}{\gamma m}[G\gamma \vec{B}_{\perp} + (1+G)\vec{B}_{//}] \times \vec{S}$$

Spin vector in particle's rest frame

Magnetic field along the direction of the particle's velocity

Magnetic field perpendicular to the particle's velocity

- G is the anomoulous g- factor, for electron, G~0.00116
- γ: Lorenz factor

note

this leaves out the electric field effect on spin motion

Definition: Spin tune $Q_s = G\gamma$, is the number of precession per orbital revolution

Depolarizing mechanism in a circular accelerator

In a planar circular accelerator, the horizontal magnetic fields perturb the spin precession around vertical direction. As the beam goes around the ring, when these perturbations add up coherently, polarization can be lost, i.e. depolarizing resonance.

Imperfection resonance

- comes from dipole error and quadrupole misalignment
- locate at $G\gamma = k$, where k is an integer
- strength proportional to vertical closed orbit distortion

Intrinsic resonance

- comes from betatron oscillation in the vertical plane
- locate at $G\gamma = kP \pm Q_y$, where k is an integer, P is the periodicity and Q_y is the vertical betatron tune
- strength proportional to amplitude of vertical betatron oscillation

Polarized electrons in a synchrotron

- Sokolov-Ternov effect: self-polarization of charged particles in a planar circular accelerator through the emission of spin flip from synchrotron radiation. Most effective for e^+ and e^-
- first predicted by Ternov,and Sokolov by rigorously solving Dirac equation
- the polarization build-up time is

$$\tau_p^{-1} = \frac{5\sqrt{3}}{8} c\lambdabar r_e \gamma^5 \langle |\rho^{-3}| [1 - \frac{2}{9}(\vec{\beta}\cdot\vec{n})^2] \rangle$$

where, r_e is the electron classical radius.

- and the equilibrium polarization can be reached is

$$P_\infty = \frac{8}{5\sqrt{3}} \frac{\langle |\rho^{-3}| \hat{n}.\hat{b} \rangle}{\langle |\rho^{-3}| [1 - \frac{2}{9}(\vec{\beta}\cdot\vec{n})^2] \rangle}$$

Spin diffusion

However, the synchrotron radiation also introduces quantum excitation, which in turn makes sudden energy change and increases the betatron amplitude. This then introduces depolarizing, aka Derbenev-Kontrotenko depolarizing effect. This limits the achievable polarization for high energy electron accelerators.

This table enlists the achieved polarized electron facilities

	VEPP[10]	VEPP2-M[11]	ACO[8,9]	BESSY[44]	SPEAR[45]	VEPP4[46]
E(GeV)	0.640	0.625	0.536	0.800	3.70	5.0
τ_p(min)	50	70	160	150	15	40
P(%)	52	90	90	>75	>70	80
	DORIS II[47]	CESR[48]	PETRA[49]	HERA[19]	TRISTAN[50]	LEP[51]
E(GeV)	5.0	4.7	16.5	26.7	29	46.5
τ_p(min)	4	300	18	40	2	300
P(%)	80	30^*	80^{**}	70^{**}	75^{**}	57^{**}

Depolarizing resonance in SPERA

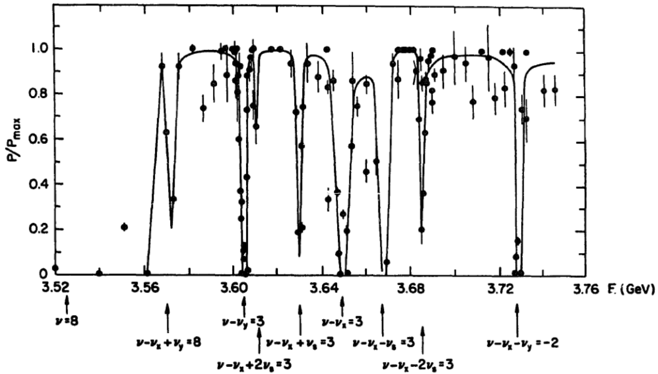
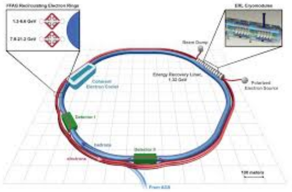


Fig. 1. Polarization measurements at SPEAR (from ref. [2]). The quantity P_{max} is $8/(5\sqrt{3}) = 92.4\%$. The curve is a guide for the eye, not a theoretical calculation. Various resonances have been identified in the data. The orbital tunes are called $\nu_{x,y,s}$ instead of $Q_{x,y,s}$. The spin tune is ν. A single beam of positrons was circulated when making measurements. The graph is not a single experiment, but a compilation of many runs.

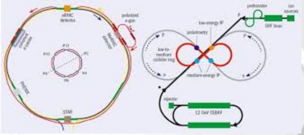
Future accelerator facilities with polarized electrons

- Electron Ion Collider

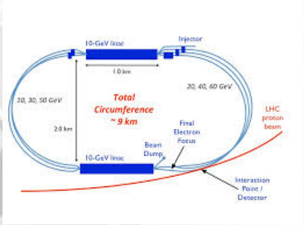
eRHIC



MEIC

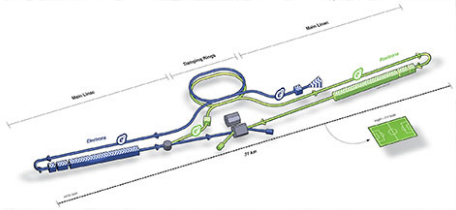


LHeC

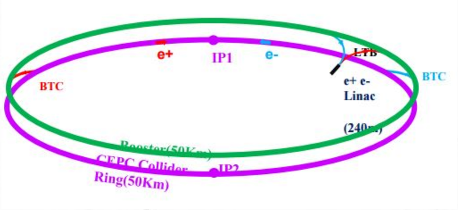


- e+e- collider

ILC

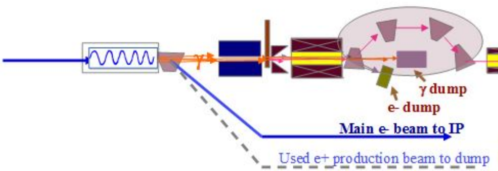


CEPC



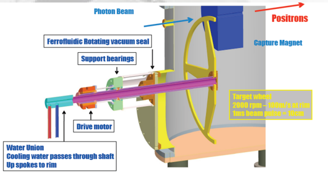
Challenges in high energy polarized e+e- beams

- for linear collider: high energy polarized positrons



Gai, ILC electron and positron sources
http://www.fnal.gov/directorate/ILCPAC/2012Dec/pac12kek-wg-12-10-Gai.pptx

  - undulator based polarized positron production
  - several challenges in photon collimation as well as target, a Titanium alloy rotating wheel with rims moving at 100m/s



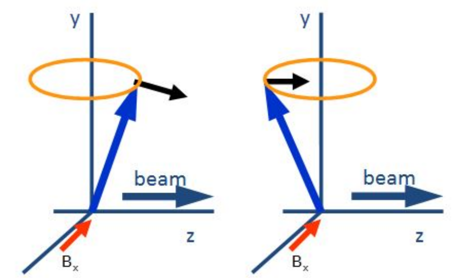
- for high energy circular e+e- collider: effective spin rotator for preserving polarization (Siberian snake) as well as providing longitudinal polarization for experiment

Accelerating polarized hadron beams to high energy

overcome depolarizing resonances

- for low energy and medium energy accelerator, one can apply corrections at each individual resonance
  - imperfection resonance
    - ★ harmonic orbit correction
    - ★ partial Siberian snake
  - intrinsic resonance:
    - ★ tune jump to minimize polarization loss
    - ★ RF dipole: excite coherent betatron oscillation to induce full spin flip
- for high energy accelerator: **full Siberian snake**

a device that rotates spin vector by 180°, which in turn keeps the spin tune independent of energy



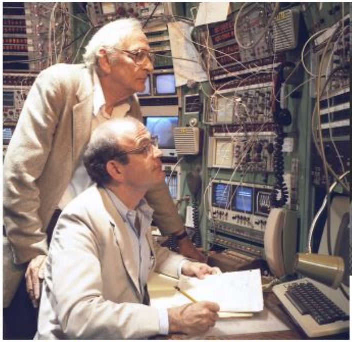
Brief history of high energy polarized protons

- 1969-1973, first 12 GeV/c polarized proton beam was achieved in ZGS with orbit harmonic correction and fast tune jump
- 1973 concept of Siberian snake proposed by Derbenev and Kondratanko [Sov.Phys.JETP 37:968-973,1973, Zh.Eksp.Teor.Fiz 64:1918-1929]
- mid 1980s, the concept of snake was experimentally demonstrated at the IUCF Cooler Ring
- early 1990s, using partial snake to overcome imperfection resonance [T. Roser, Proc. Workshop on Siberian Snakes and Depolarizing Techniques, 1989, p. 1442]
- 2000s, polarized protons reached 250GeV with 60% average store polarization at RHIC

Brief history of high energy polarized protons

Brookhaven AGS : 1974~present

1980s



Alan Krisch and Larry Ratner in the AGS MCR.

~ 40% polarization at 22 GeV, **7 weeks** dedicated time for setup

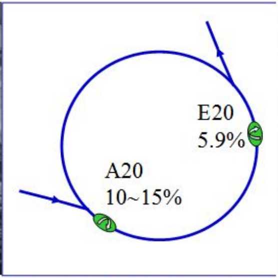
1990s

5% snake +RF dipole

~ 2 weeks setup parasitic to RHIC Ion program

50% at 24 GeV

2006 - now



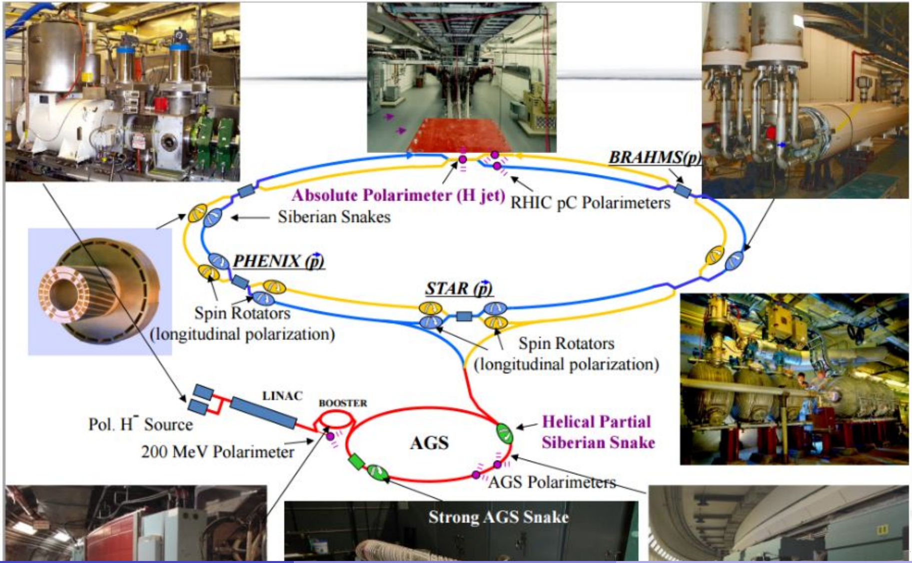
6% warm helical snake
+10% cold helical snake

~2 weeks setup

65%-70% at 24 GeV

Achieved performance of polarized protons

RHIC as the world's only high energy polarized proton collider is equipped with dual snakes and outstanding beam control



Preserving polarization in RHIC

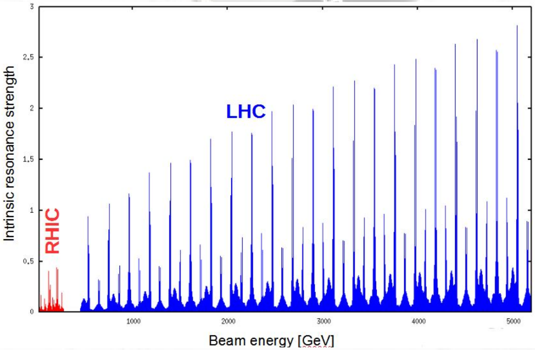
- snake resonance [S.Y Lee, S. Tepikian]: polarization loss at the neighborhood of an intrinsic spin resonance when $mQ_y = Q_s + k$
- to avoid snake resonance
  - optimze snake setup to make spin tune as close to 0.5 as possible
  - careful choice of betatron tune to avoid locations of snake resonance
  - precise beam control
    - betatron tune excursion
    - global closed orbit distortion
    - local orbit at snake as well as spin rotator to minimize spin tune shift as well as spin tune spread
- **achieved 60% polarization at 250 GeV/c with 2×10^{11} protons per bunch**

outlook of polarized hadrons

Energy frontier: polarized protons goes beyond RHIC energy

- the higher energy, the stronger depolarizing resonances
- For LHC, it requires multiple pairs of Siberian snakes in addition to accelerate polarized protons through its chain of injectors

at LHC, the resonances become so strong that the tolerance on beam and machine parameter has to go order of magnitude below what RHIC has achieved ($< 100\mu$ m closed orbit distortion, and 10^{-3} betatron tune)



- T. Roser The Future of High Energy Polarized Proton Beams, Spin Symposium, 2008, Charlottsville, VA

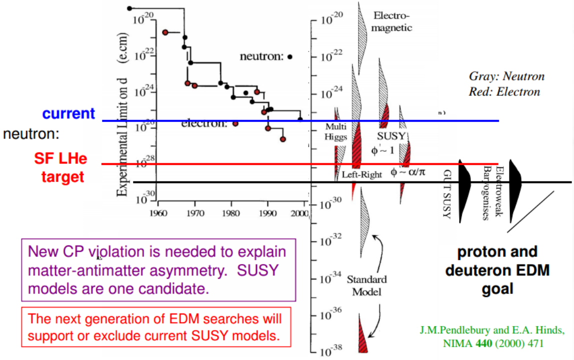
‘

outlook of polarized hadron beams

precision frontier: hunt of Electric Dipole Moment

- motivated by the fact that our current observation of CP-violation is insufficient to explain the asymmetry between matter and antimatter

- great progress made over the decades in measuring the electric dipole moment of electrons, neutrons,etc.



- **However, so far, there is no direct measurement of charged particles, proton, deuteron, etc**

Challenges of EDM storage ring

- First proposed by srEDM@BNL to measure proton and deuteron EDM in a storage ring: spin frozen method [https://www.bnl.gov/edm/]
- requires polarized beam with long lasting spin coherence time as well as high precision polarimetry with high efficiency
  - E. Stephensen's presentation in session 1, and I. Keshelashvili's presentation in session 5
- remaining challenges
  - understanding of various systematic errors
  - high precision beam position monitor development
  - high precision beam control
  - high field electrostatic deflector development for proton or electron
    - ★ to fit in current COSY tunnel, an electrostatic deflector with $> 15 MV/m$ strength is required
  - hybrid electric and magnetic field deflector for deuteron
    - ★ requires not only extreme stability of the electrodes, but also high precision magnetic field if the polarity is reversed
  - magnetic shielding for All-electrostatic storage ring
- update on the status of Juelich EDm Invesitgation collaboration (JEDI), Prof. Lehrach in session 11

Summary

- Polarized beams have been widely used in the understanding of fundamental structure of matter as well as other applications
- High energy polarized beams enable more fascinating studies in understanding
  - proton spin structure
  - CP violation
- high energy polarized beams at future facilities open more exciting studies with more challenges
  - polarized positron source
  - high energy polarized electron beam spin rotator
  - polarized He-3 beams
  - precision frontier storage ring for direct EDM measurement

Thank you, and wish you a very successful workshop on Polarized Source, Target and Polarimetry!